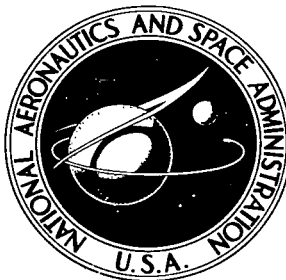


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THE INFLUENCE OF FIXTURE STRESS CONCENTRATIONS ON RING ACCELEROMETERS

by James A. Nagy and Charles E. Henley, Jr.

*Goddard Space Flight Center
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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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ABSTRACT

Tests have revealed that the most commonly used accelerometer at the Goddard Space Flight Center can be subject to a subtle source of error from strains developed in vibration fixtures. Accelerometers mounted on supposedly rigid surfaces may show errors on the order of 100 percent at the very low frequencies below any resonances.

A study was initiated to determine the nature of the fixture stress concentration and means of avoiding it. This paper describes the test methods used during the study and the results obtained. The test methods discussed include standard accelerometer calibration techniques; calibrations varying torque, position, and mounting hole angle; photoelastic techniques; base sensitivity checks; and tests with a transducer devised to detect the presence of base-strain in mounted accelerometers.

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INTRODUCTION

This paper presents the results of an investigation of accelerometer base-strain sensitivity. This investigation was precipitated by anomalies experienced during lateral-vibration tests of heavy spacecraft where a large moment tends to tip a circular base about a point. The load is transferred to the test fixture and produces stress concentrations around the mounting hole for the shaker control accelerometer. The test fixture does not bend appreciably; nevertheless, the stress concentrations produce the same spurious output as that obtained from the accelerometer when its base is subjected to bending on a cantilever beam. Base bending produces an erroneous accelerometer output proportional to the bending strains.

APPARATUS AND TESTS

Piezoelectric ring-shaped shear accelerometers are the most commonly used at the Goddard Space Flight Center for shaker control and response measurements during vibration tests. (See Figure 1.) For shaker control, the accelerometer is screwed directly to the test fixture alongside a control monitor accelerometer. During certain spacecraft vibration tests, there was disagreement between these two accelerometers at low frequencies below resonance. The cause was unknown, since the fixture was not subject to bending. Moreover, the accelerometer's shear design is intended to isolate the crystal element from base bending and case distortion. Inconsistent results from the two accelerometers frustrated early investigators, but the anomaly was circumvented by mounting the accelerometers on a block welded to the fixture which relieved the stress concentrations. Recent similar test inconsistencies have revived the study of the problem.

An old Goddard fixture known to have caused erroneous accelerometer outputs was used for this investigation. The fixture is an 18-inch aluminum disk, 2-inches thick, which picks up a C-125 shaker-hole pattern. Figure 2 shows the simulated spacecraft lateral test setup to check the fixture control accelerometer location for base strain. Acceleration was controlled at the shaker with a base-strain free accelerometer to 0.5g peak from 8 to 100 Hz while recording response at location 2 (the control point used in past tests).

The response accelerometer should have agreed with the control accelerometer at the low frequencies below resonance; but it did not, as shown in Figure 3. It was further found that its output was a function of mechanical rotation of the accelerometer about its sensitive axis, as shown by

the two curves and the response marks at 20 Hz for other orientations. It was now obvious why inconsistencies had frustrated the earlier investigators; but it was not understood why the accelerometer output was orientation-sensitive and apparently frequency-dependent.

To prove the existence of base-strain it was decided to desensitize the accelerometer to the point where it would ignore acceleration and have an output due solely to fixture stresses.

A cutaway display model of the ring accelerometer showed that if strain gauges were bonded to the accelerometer's post assembly, this might provide a transducer suitable for detecting base-strain. Luckily, a post had been obtained from the manufacturer several years ago when these spurious outputs were first observed (Figure 4). The post was instrumented and installed in location 2 on the fixture. A static strain output was obtained during the installation of the post and a dynamic output was obtained from 20 to 60 Hz as the simulated spacecraft

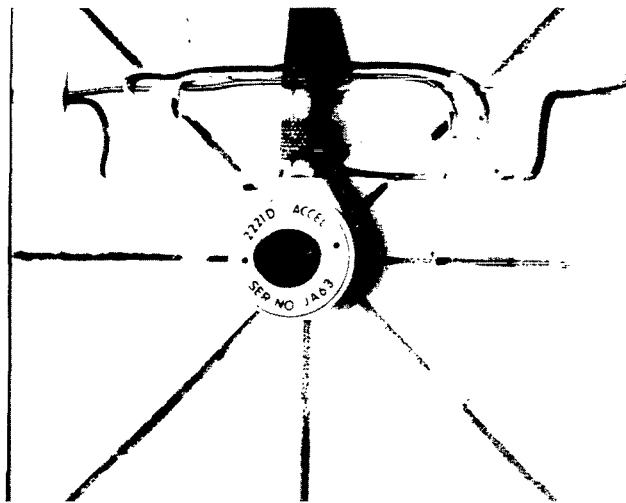


Figure 1—Piezoelectric ring-shaped shear accelerometer.

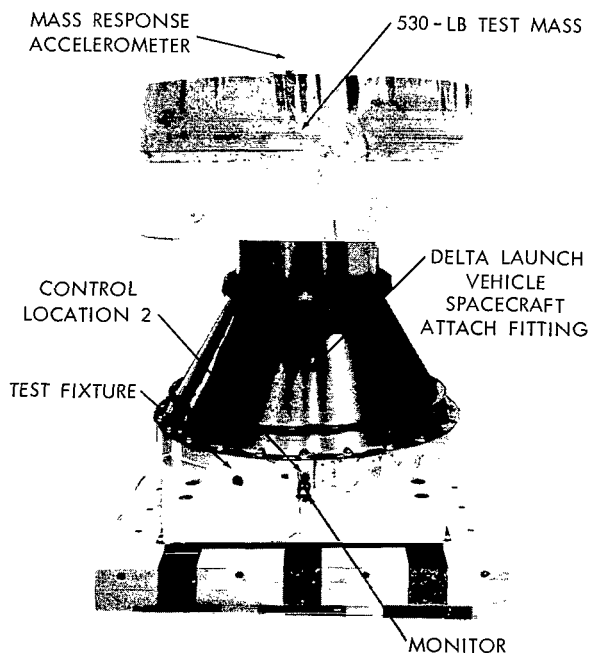


Figure 2—Fixture mounted for lateral vibration.

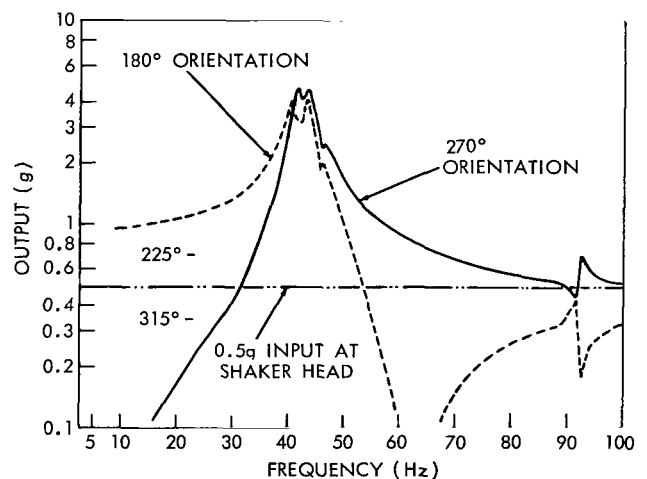


Figure 3—Filtered composite response of 221D at location 2.

mass went through resonance during a 0.5g sine sweep. The existence of fixture strain had been proved; now it was decided to investigate the accelerometer's base-strain characteristics.

BASE-STRAIN SENSITIVITY TESTS

Nine ring accelerometers of the same manufacture were randomly chosen from stock and calibrated. Frequency-response and amplitude linearity were carefully checked. In the absence of base-strain, the accelerometers' frequency response and amplitude linearity were insensitive to mounting torque, orientation, and installation in misaligned holes.

The accelerometers were then tested for base-strain sensitivity (Figure 5), using the test method described in ISA Standards RP 37.2, paragraph 6.6, (Reference 1) as follows: "The technique used to measure strain sensitivity of an accelerometer meets the requirement of ASA Z 24.21-1957 [Reference 2] (General Reference C) paragraph 3.1.3.7. The accelerometer is mounted on a simple cantilever beam. The radius of curvature at the point where the accelerometer is mounted is 1000 inches when the beam measurements are taken. A steel beam is held as a cantilever in a vice (sic) bolted to a concrete floor. The beam is 3.0" wide by 0.5" thick and 60" long. (The free length is approximately 57 inches.) The natural frequency is very close to 5 cps. Four strain gauges are bonded to the beam adjacent to the accelerometer mounting hole (two each, top and bottom, about 1.5" from the edge of the clamp). A two-channel recorder is used to record the output of both the strain gauge bridge and the accelerometer under test. The system is excited by manually deflecting the free end of the beam and allowing it to vibrate freely. The output of the accelerometer is taken from the oscillograph record at a point where the strain in the surface of the beam is 250×10^{-6} inch per inch. (This is equivalent to a



Figure 4—Instrumented ring accelerometer post.

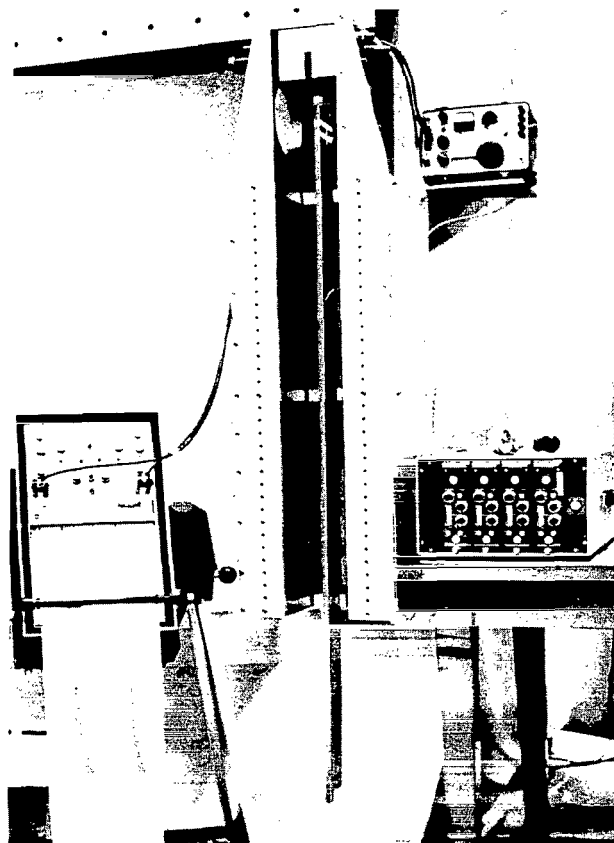


Figure 5—Base-strain sensitivity setup.

radius of curvature of 1000 inches.) The strain sensitivity, in g's, for a strain of 10^{-6} inch per inch is found by dividing the accelerometer output by 250 times the accelerometer sensitivity in millivolts per g." The results are summarized in Table 1 and show that the strain sensitivity for the nine accelerometers varied from an equivalent $0.008 \text{ g}/\mu \text{ in./in.}$ to $0.04 \text{ g}/\mu \text{ in./in.}$ Mounting torque was 10 in. lb. The manufacturer recommends 8- to 12-in. lb torque; his strain data indicate a nominal strain sensitivity for the 2221 D as $0.03 \text{ g}/\mu \text{ in./in.}$ He does not mention torque sensitivity; however, ring accelerometer output due to base-strain proved sensitive to torque.

Figure 6 shows a typical record of accelerometer output versus beam strain obtained from the beam test. This particular record does not show the magnitude effect of orientation, but does show that the accelerometer's output polarity changes with orientation when base strain is present. Note that in the 45-degree position, the accelerometer's output is in phase with beam strain; in the 90-degree position, it is out of phase. This can be detected with the first pull of the beam.

Figure 7 shows the output of the accelerometers plotted as a function of rotation about the sensitive axis. Note that the outputs are not symmetrical about zero, that measurements were made every 45 degrees, and that it takes four measurements to define maximum positive and negative strain sensitivity. These plots indicate that the accelerometer is orientation-sensitive to beam strains and that two cycles are generated for each complete cycle of mechanical rotation. It would seem that the accelerometer is strain-sensitive along two axes, 90 degrees apart and perpendicular to the sensitive axis. When the beam is deflected, a strain is produced along the beam length; however, due to Poisson's effect, a strain of opposite sign is produced across

Table 1
Strain Sensitivity Summary.

| Model | Maximum Strain Sensitivity* | Mounting Torque Effect on Strain** Sensitivity Equivalent $\text{g}/\mu \text{ in./in.}$ | | |
|--------|---|---|-----------|-----------|
| | Equivalent $\text{g}/\mu \text{ in./in.}$ | 5 in.-lb | 10 in.-lb | 15 in.-lb |
| 2221 C | 0.02 | 0.008 | 0.02 | 0.03 |
| 2221 C | 0.04 | 0.02 | 0.03 | 0.04 |
| 2221 D | 0.008 | 0.003 | 0.006 | 0.008 |
| 2221 D | 0.03 | 0.01 | 0.02 | 0.03 |
| 2221 D | 0.02 | 0.02 | 0.02 | 0.02 |
| 2221 D | 0.04 | 0.02 | 0.03 | 0.04 |
| 2221 E | 0.01 | 0.007 | 0.01 | 0.02 |
| 2221 E | 0.01 | 0.008 | 0.01 | 0.01 |
| 2221 E | 0.04 | 0.02 | 0.03 | 0.04 |

*Maximum strain sensitivity for 10 in. lb mounting torque.

**Torque sensitivity test carried out at the approximate orientation producing maximum strain sensitivity.

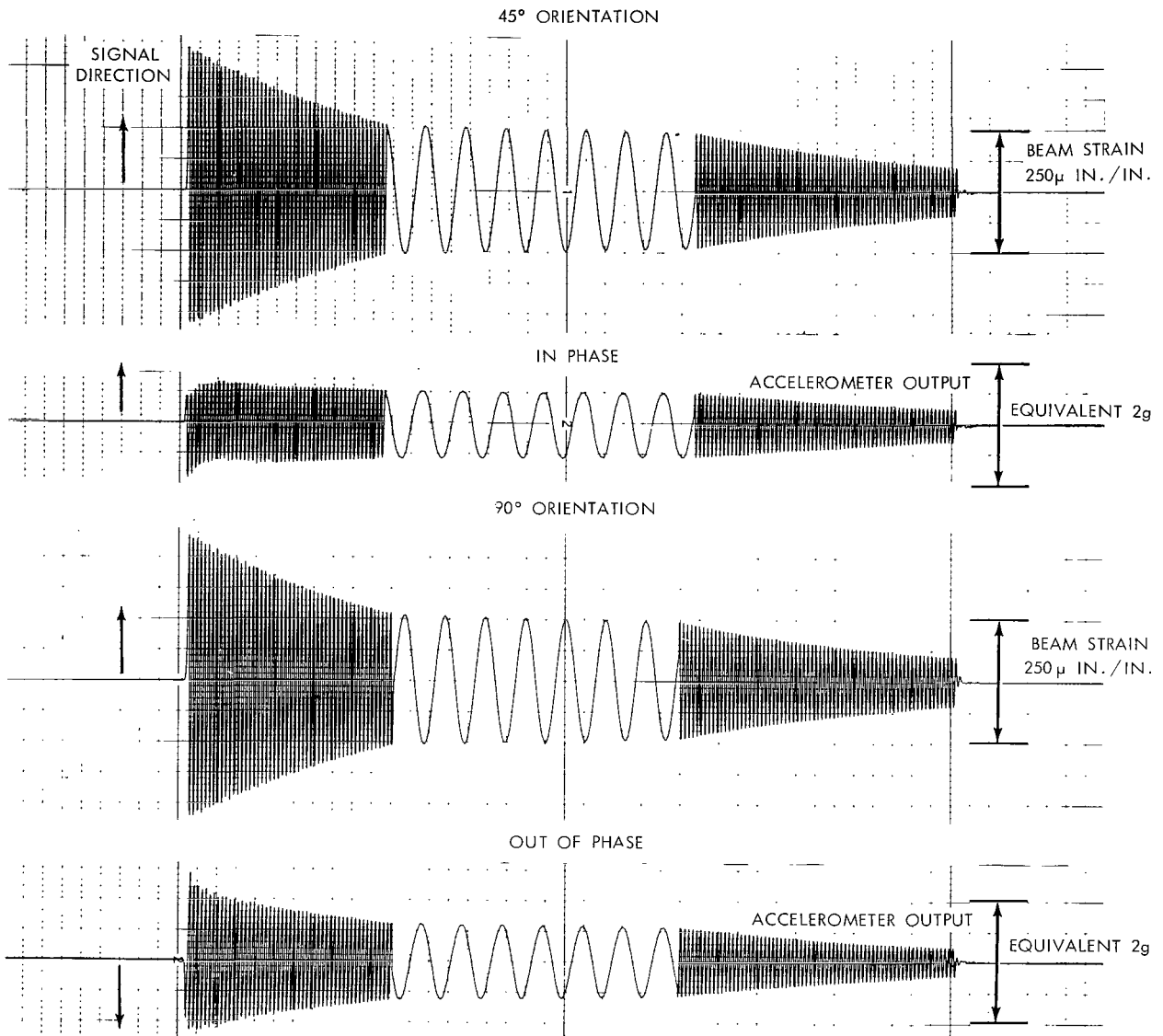


Figure 6—Typical record for strain-sensitivity determination.

the beam. As the accelerometer's x and y sensitive axes are rotated through this 90-degree strain field, a resultant sinusoidal output is generated which produces two cycles per cycle of rotation.

STRAIN-ONLY FIXTURE TEST

Although the strain sensitivity had been determined on the beam with no appreciable acceleration in the accelerometer's sensitive axis and no cross-axis acceleration, it was felt that the same absence of acceleration conditions should be duplicated with the simulated spacecraft lateral

test setup. This was accomplished by rigidly attaching the fixture to the floor of the shaker cell (Figure 8). The shaker armature was coupled to the top of the mass and driven at 7 Hz to produce the required moment. Shaker displacement was held at 0.05 in. D.A. A vertically oriented strain gage was mounted on the fixture plate 180 degrees away from location 2 to verify strains produced in the fixture. The results from this test were the same as those obtained on the beam. The five accelerometer locations shown, as well as the two on the plate beneath, showed varying degrees of base strain. Location 2 produced the highest output because of its proximity to the attach-fitting bolt carrying the greatest load due to moment. A constant-displacement frequency sweep was conducted from 5 to 100 Hz; it showed

that the accelerometer's strain sensitivity was not frequency-dependent. It was further shown that an accelerometer could be so oriented that it would produce virtually no output due to base strain on this particular fixture.

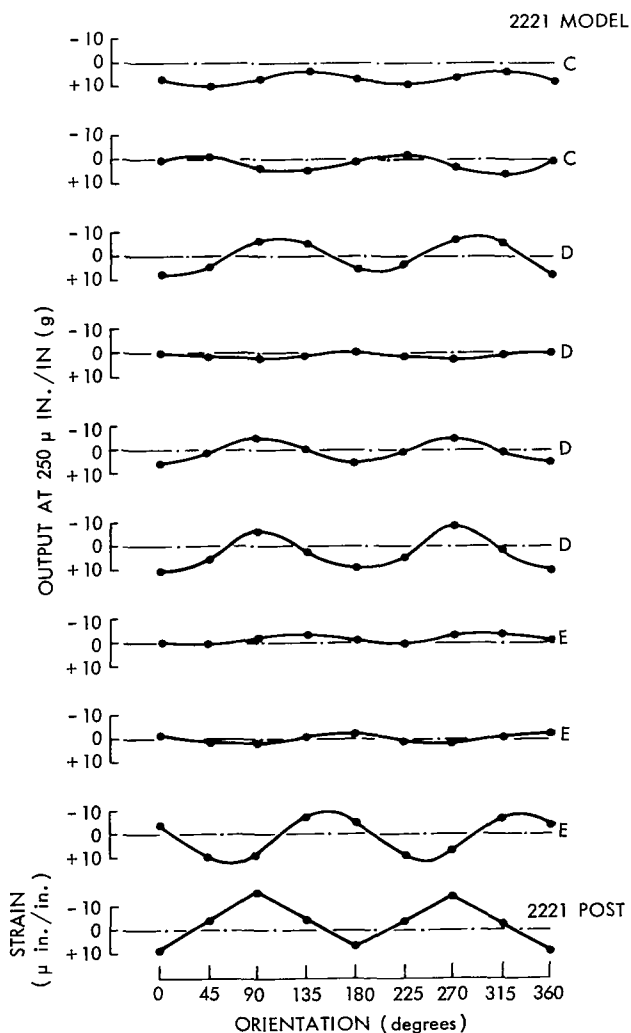


Figure 7—Accelerometer strain output as a function of rotation about its sensitive axis.

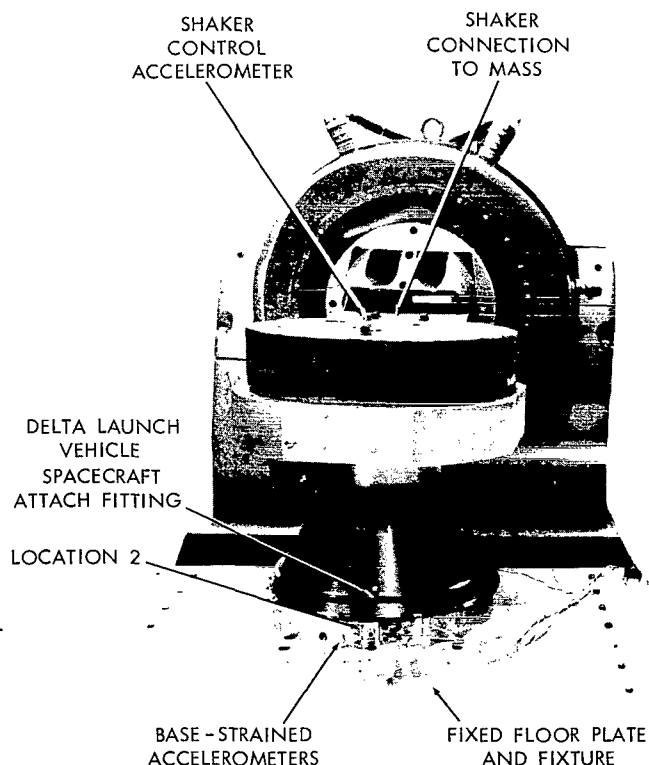


Figure 8—Test setup for fixture strain verification.

VIBRATION TEST

It was now felt that enough information was available to permit a return to the lateral vibration test of Figure 2 and understand the results; with an understanding of base-strain, we could produce an overttest or undertest at will on the simulated spacecraft. To illustrate the effect on base-strain free control for this test, a 2224C top connector shear accelerometer was tested on the beam to confirm the manufacturer's nominal figure of $0.0005/\mu$ in./in. The accelerometer's maximum strain sensitivity was found to be $0.0005g/\mu$ in./in. It was then mounted to the beam with a model 2986 insulated stud and showed no measureable output for a beam strain as high as 400μ in./in.

The plots in Figure 9 show the response at the top of the mass for three separate tests when the shaker was controlled at location 2 with strained and strain-free accelerometers. The first run was made with the strain-free 2224C mounted on the stud at location 2 to show the simulated spacecraft response with a true input. All sweeps were made at 0.5g. The next run was made with the base-strained ring accelerometer mounted at location 2 and oriented at 180 degrees to produce a positive strain signal, thereby adding to the acceleration signal and resulting in an overttest. The last run was to show that an overttest would result. The ring accelerometer was re-oriented to 270 degrees to give a negative strain signal, which cancelled out the acceleration signal. When the shaker control system was turned on at 7 Hz, the servo-system saw no acceleration signal, with the result that it increased the shaker level until the amplitude protector was energized and a dump occurred. The test was then repeated by a sweep down from 100 Hz until the amplitude protector dumped. This response may be incorrect, because the spacecraft attach fitting cracked in many places in the vicinity of location 2 and at 180 degrees away. In Figure 9, note that at the true resonance frequency of 45 Hz, the mass will change phase approximately 180 degrees with respect to the control accelerometer. Therefore, if acceleration and strain are in phase below resonance, they will be out of phase above resonance, and vice versa. In addition, note the false spacecraft resonant frequency indicated when the shaker control accelerometer is subject to base-strain.

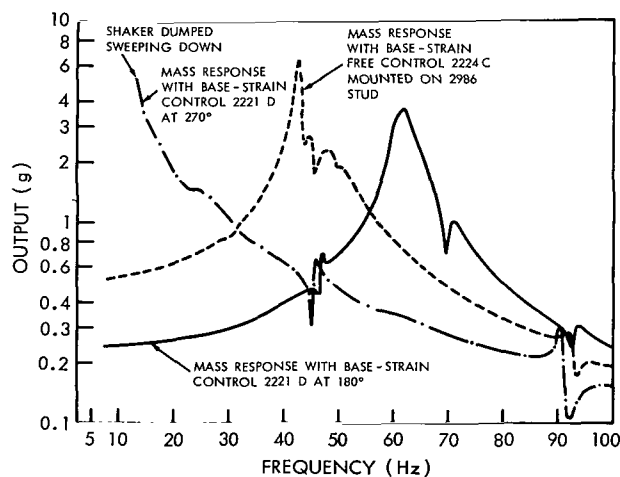


Figure 9—Filtered-mass response with strained and strain-free shaker control accelerometer mounted at location 2.

ADDITIONAL OBSERVATIONS

Several other observations were made and some conclusions drawn:

1. Accelerometer screws made from four different materials were tested to determine their effect on strain sensitivity. Beryllium copper screws decrease strain sensitivity, but the difference is not of practical significance.
2. The ASA technique for determining strain sensitivity should be modified, since the accelerometer's strain-sensitive axes might be so aligned as to produce no output due to base-strain. The ASA technique should state that at least four measurements are required to define maximum strain sensitivity. The accelerometer should be mechanically rotated through 45 degrees for each measurement.
3. Manufacturer's quoted figures on base-strain sensitivity are suspect unless it is stated that the maximum strain sensitivity has been determined by the rotation technique.
4. Photoelasticity was attempted as a means to study the stress pattern around the accelerometer mounting hole; but the stresses were so low that the photoelastic material's threshold was reached and the results were unsuccessful.
5. Local stress concentrations exist around the hole in the bending beam; this means that the accelerometer does not experience the strain indicated by the strain gage. (The problem is only of academic interest if all laboratories follow the ASA test method.)
6. These results show that correlation between two accelerometers mounted side-by-side does not prove that they are free of base-strain effects.
7. The results from this investigation point out that base-strain could be the answer to the following vibration test anomalies:
 - a. The same or similar test item passes a vibration test on one shaker and fails on another.
 - b. The same or similar test item passes a vibration test once and fails next time on the same shaker.
 - c. Shaker dumps occur at low frequency or at resonance.
 - d. Accelerometers mounted side-by-side do not agree at low frequencies or at resonance.
 - e. Poor shaker control exists during low-frequency resonances with an apparent lack of sufficient shaker compressor speed and a loss of signal at the shaker console.
 - f. Random equalization of resonances is difficult or impossible.
 - g. Resonances of the same or similar item seemingly shift frequency and change transmissibility under similar test conditions.

CONCLUSION

Piezoelectric ring-type shear accelerometers have a spurious output not only due to a bending surface but also due to accelerometer-mounting hole-stress concentrations. All accelerometers should be suspected of base-strain until proved otherwise. Extra care should be given to the mounting location and use of a shaker control accelerometer if reliable test results are expected. Since some accelerometer manufacturer's data sheets state that the ring accelerometer provides complete mechanical isolation of the sensing element from mounting strains, we should like to reiterate B. Mangold's recommendation presented at the 35th Symposium,

"Therefore, it is recommended that the accelerometer suppliers because of their unique qualifications, update their data sheets to include information concerning base-strain sensitivity, temperature-transient sensitivity, and any other properties heretofore unpublished which may be of considerable value to the accelerometer users." (Reference 3.)

It would be helpful if the manufacturer's product sheets and sales literature on the general subject of shear accelerometers would clearly state the base-strain sensitivity.

ACKNOWLEDGMENTS

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Goddard Space Flight Center
National Aeronautics and Space Administration
Greenbelt, Maryland, December 5, 1967
124-08-05-03-51

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